Comparison of Zgoubi and S-Code regarding the FFAG muon acceleration

J. Fourrier, S. Machida

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J. Fourrier

IN2P3, LPSC Grenoble

S. Machida

Rutherford Appleton Laboratory

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Abstract

Contents

1 Introduction

The high flux accelerator based neutrino source is foreseen as one of the next generation facilities of particle physics.Called Neutrino Factory (NuFact), it will be based on a muon storage ring where muons will decay , creating high flux neutrino beams. Muons are supposed to be accelerated from 5 to 20 GeV before being injected into the storage ring. In that purpose, Fixed Field Alternating Gradient accelerators (FFAG in the following) are one of the possibilities.

Cell designs have been done and tracking studies are on their way using codes such as MAD, S-Code or Zgoubi. In order to cross-check results so obtained, we have performed comparisons between S-Code and Zgoubi at Rutherford Appleton Laboratory. The present report will explain the different simulations done and the results.

2 Time of Flight comparisons

The time of flight refers to the particle revolution time around the ring. One of the parameters it depends on is the initial coordinate in transverse phase space (horizontal or vertical). The study has been the following: several particles have been tracked around the ring using both Zgoubi and S-Code and time of flights of these particles have been compared. In particular, both codes have been used to compare time of flights of one muon moving on the closed orbit (at 5 GeV) and of other particles with initial coordinates taken on a 30 π mm rad ellipse.

The surface of the beam in the transverse phase space is considered as shown below. The emittance ϵ is defined as surface = π ϵ and the normalized emittance is $\epsilon_N = \beta\ \gamma\ \epsilon$, with $\beta = \frac{v}{c}$, $\gamma = \frac{1}{\sqrt{1-\beta^2}}$

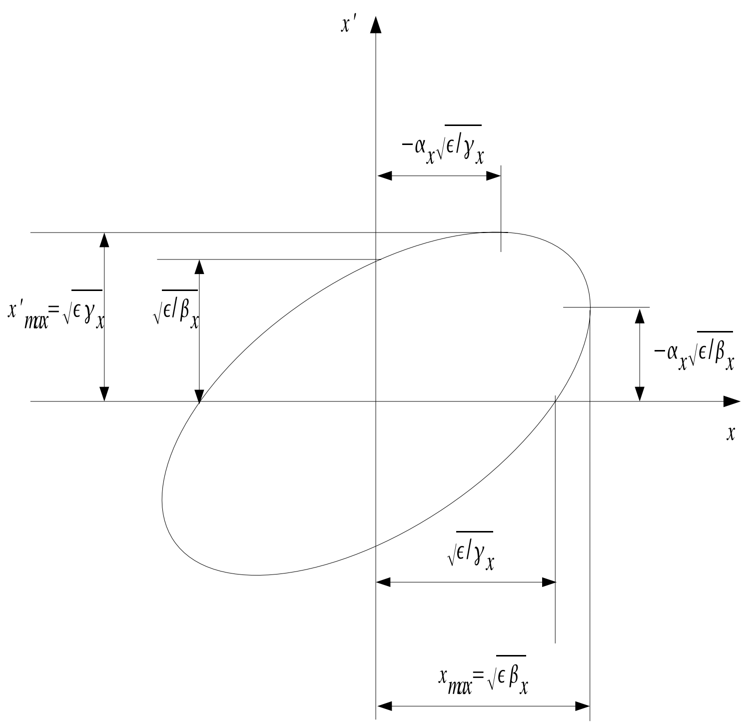


Figure 1: Parameters of a phase-space ellipse containing an emittance ϵ.

The initial normalized transverse emittance is ϵ_N = 30 π mm rad. The beam parameters α_y, β_y of the cells have been calculated with Zgoubi for the 5 GeV and the 10 Gev closed orbits respectively in the 5-10 GeV FFAG and 10-20 GeV FFAG.

	$\epsilon_{N,x,z}$ (m.rad)	$\beta\,\gamma$	$\epsilon_{x,z}$ (m.rad)	α_x	β_x $(m.rad^{-1})$	α_z	β_z $(m.rad^{-1})$
5 GeV	3 10^{-2}	47.311	6.341 10^{-4}	-1.883	2.424	1.639	3.555
10 GeV	3 10^{-2}	94.638	3.170 10^{-4}	-2.077	2.820	1.727	4.313

Table 1: Transverse beam parameters for the 5 GeV and 10 GeV initial distribution.

Zgoubi tracking code required initial coordinates of the particles as input data. Thus, they have to be calculated from the coordinates of a particle moving on the closed orbit (taken as a reference particle) and α_y, β_y parameters. The ellipse centered on the average orbit (X_0, X_0') is defined with the following equation in the machine referential system $(R_{machine})$:

$$\gamma_x(X - X_0)^2 + 2\alpha_x(X - X_0)(X' - X_0') + \beta_x(X' - X_0')^2 = \epsilon_x$$

Let's $x = X - X_0$, $x' = X' - X_0'$, (x, x') be the particle coordinates in the closed-orbit-particle referential system (R_1). The ellipse equation becomes the following:

$$\gamma_x x^2 + 2\alpha_x x x' + \beta_x x'^2 = \epsilon_x$$

Reference particle (moving on the closed orbit) coordinates (X_0, X_0') are calculated with the help of Zgoubi.

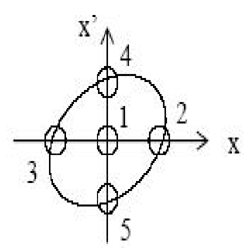


Figure 2: Particles around the ellipse.

Let's consider particle number 2 with initial coordinates $(x_2, 0)$ in R_1 and (X_2, X_2') in $R_{machine}$

$x_2 = \sqrt{\frac{\epsilon_x\beta_x}{1+\alpha_x^2}}$, $x_2' = 0$ in R_1

$X_2 = x_2 + X_0$, $X_2' = x_2' + X_0'$ in $R_{machine}$ and for Zgoubi input data files.

$x_3 = -x_2$, $x_2' = 0$

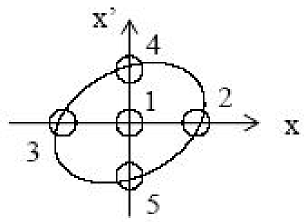
$x_4 = 0$, $x_4' = \sqrt{\frac{\epsilon_x}{\beta_x}}$

$x_5 = 0$, $x'_5 = -x_4$

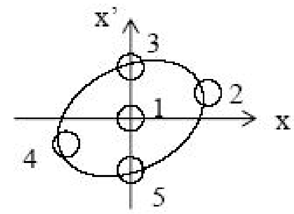
In the same way than for the particle number 2, initial coordinates for particles number 3,4,5 are obtained with a translation (X_0, X'_0) in the transverse phase space.

The muon machine cell is the following: long drift / QF / short drift / QD / long drift; and the ring is made of 64 identical cells. Zgoubi and S-Code have been runned to calculate the time of flights of these 5 particles around the ring.

Zgoubi Results



S-Code Results



PID	Trev	ΔTrev
1	.964504	
2	.964807	.000303
3	.964819	.000315
4	.964813	.000309
5	.964804	.000303

PID	Trev (μs)	ΔTrev
1	.950106	
2	.950416	.000310
3	.950406	.000300
4	.950398	.000292
5	.950394	.000288

Figure 3: Time of flight comparison.

CONCLUSION

The difference of time of flight between the particle 1 and the others is comparable from Zgoubi to S-Code. Nevertheless, further investigation is necessary to make sure we would find the same revolution time with the same initial conditions.

3 Particle acceleration with different emitances.

Let's consider the particular case of particle number 2 which has different initial coordinates on ellipses from 10 to 60 Pi mm rad. In the same way than before, initial coordinates have to be calculated for any single particle with the same technique than in Section 2. The cell is similar with an extra accelerating cavity. Zgoubi and S-Code have been used to track the particles around the ring and plot their trajectories in the longitudinal phase space. The plots from both codes make them able to be compared.

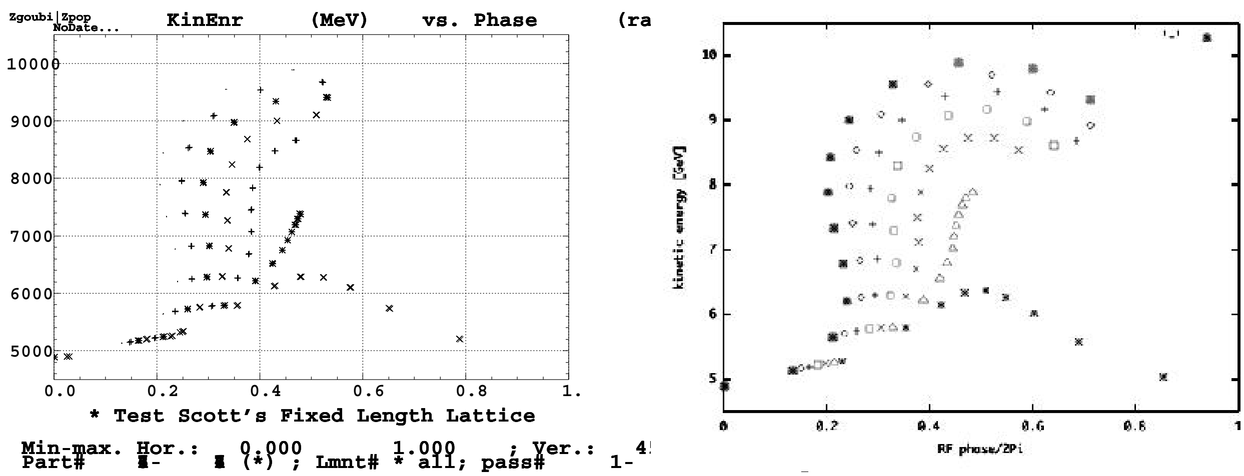


Figure 4: 5 to 10 GeV FFAG: Longitudinal phase space for particles on ellipses 10/20/30/40/50/60 π mm rad calculated with both Zgoubi and S-Code.

ACCELERATION CONCLUSION

We can see that the larger the emittance the less efficient the acceleration. Particles on ellipses 10 to 40 π mm rad are accelerated beyond 9 GeV while particles on ellipse 50 π mm rad are only accelerated up to 7.5 GeV and those on 60 π mm rad ellipse just reach 6 GeV. Thus, a beam whom emittance would be larger than 30 π mm rad would not be accelerated enough to reach 10 GeV and to be injected into the second FFAG.

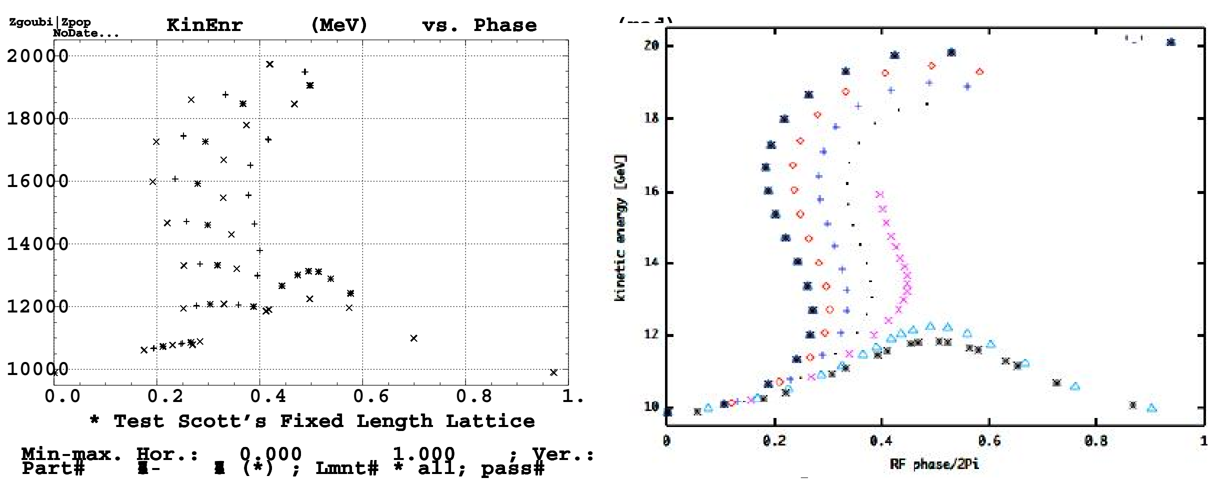


Figure 5: 10 to 20 GeV FFAG: Longitudinal phase space for particles on ellipses 10/20/30/40/50/60 π mm rad calculated with both Zgoubi and S-Code.

ACCELERATION CONCLUSION

In the same way than for the first FFAG the larger the emittance the less efficient the acceleration. Particles on ellipses 10 to 40 π mm rad are accelerated beyond 18 GeV while particles on ellipses 50 and 60 π mm rad are only accelerated up to 12 GeV. Thus, beams whom emittance is lower than 30 π mm rad could be accelerated to an energy close to 20 GeV but not enough yet. Further simulations should be done to find out if the acceleration to 20 GeV is possible.

CODE COMPARISON CONCLUSION

It is easy to manage that both codes give similar results for the longitudinal phase space. They have a good agreement which makes the results reliable.

4 Bunch acceleration

In that section, the same study is done but not only by tracking single particles but a bunch of particles with a uniform initial distribution in the three phase spaces. In our first case, the distribution in the horizontal transverse phase space is bounded in an 30 π mm rad surface ellipse and there is no spread in the two other phase spaces. Plotting the trajectories or the bunches in the longitudinal phase space shows the same shape regarding the spread of particles with different emittances. Moreover, the pictures are similar from S-Code to Zgoubi.

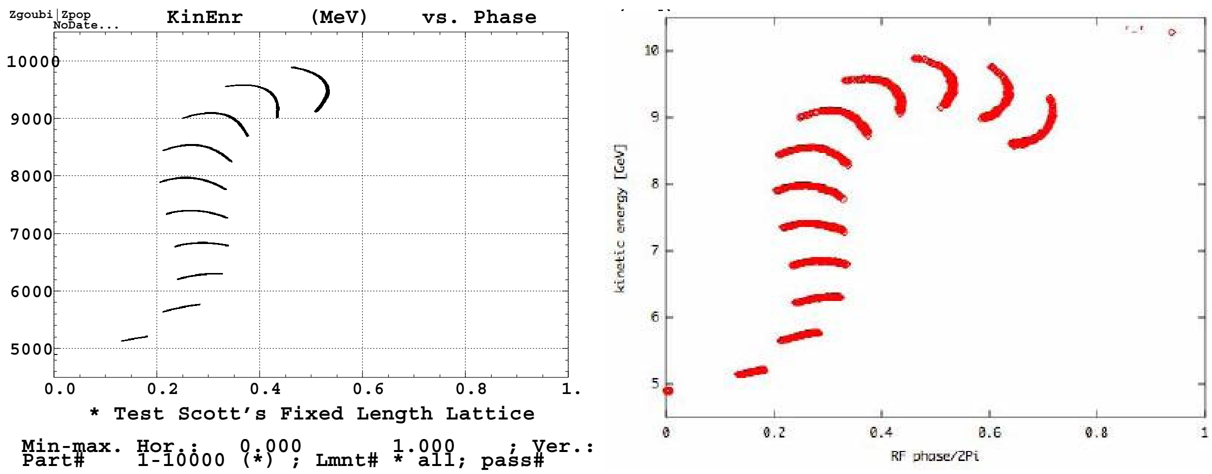


Figure 6: 5 to 10 GeV FFAG: Initial particles are filled in horizontal ellipse of 30 π mm rad. No initial spread in longitudinal or vertical.

In an other tracking study, the three phase spaces have been filled uniformely and independently with particles bounded in 30 π mm rad surface ellipses and 0.05 eV.s surface ellipse in the two transverse and the longitudinal phase space respectively.

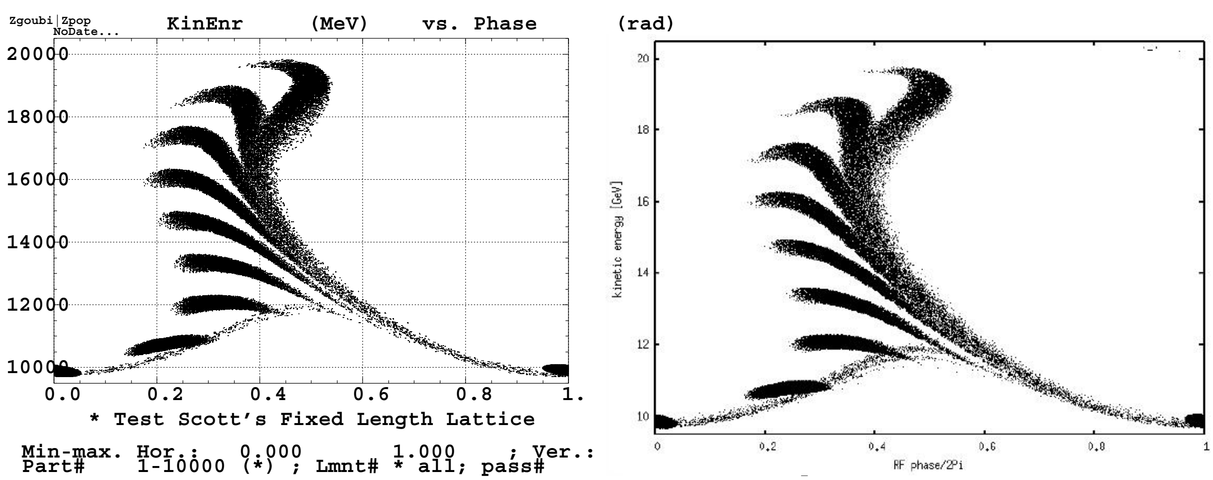


Figure 7: 10 to 20 GeV FFAG: Particles are uniformly filled in each phase space independently.

We can see that Zgoubi and S-Code have a good agreement regarding the longitudinal phase space. Both codes show a large amplitude of the bunches which could be explained by the no-correlation of the initial distribution in every phase space. Further investigation should be done with Zgoubi and S-Code.